Tidally-induced turbulent mixing in a sill fjord

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Abstract

Internal waves are generated when water currents interact with bottom topography, as when tidal flow pass across a sill in a fjord. These internal waves carry energy that is made available for turbulent mixing when the waves break.

By the use of field measurements and modeling it has been shown that the vertical mixing in different parts of the Oslofjord is caused by internal waves generated at the Drøbak Sill. The idea of a link between breaking internal waves and vertical mixing in the Oslofjord is almost 40 years old, but the details presented in this investigation are new.

The amount of energy carried by the internal waves is gradually reduced as the waves propagate inward into the fjord. When they reach the innermost part, the Bunnefjord, very little energy is left for vertical mixing. As a result of this, the deep water in this basin is stagnant for longer periods than in basins closer to the Drøbak Sill. A dramatic consequence of these physical conditions are that the oxygen concentration in the depths of the inner basin is often depleted. Thus all higher forms of life disappears. At the time of writing (December 2015), the conditions in the Bunnefjord is on the brink of reaching anoxia.

In the first paper the propagation and the loss of energy flux are described by field observations of the vertical stratification and current profiles. In the second paper details on the relation between dissipation in the vicinity of the Drøbak Sill and energy flux that radiates away from the sill, are studied with a drop sonde measuring vertical velocity shear. In the last paper energy flux is modelled with a high-resolution three-dimentional, hydrostatic model for the Oslofjord. The results clearly show the relationship between the loss of internal wave energy and vertical diffusivity.

1. Introduction

Oslo Centre for Interdisciplinary Environmental and Social Research (CIENS was established in 2006 as a collaboration between several independent institutions. Among them were three groups working with physical oceanography, one within the Norwegian Institute for Water Research (NIVA), a second within the Research and Development Department at the Norwegian Meteorological Institute (MET Norway) and a third within the Section for Meteorology and Oceanography at the Department of Geosciences, University of Oslo. In 2008 the three groups made a joint proposal to the Research Council of Norway entitled ”Tidally-induced turbulent mixing in a silled fjord”. The application was granted, and the present thesis is a direct implication of the work performed in the project.

Essential regions of the marine ecosystems along the coast of Norway are situated inside fjords. Further, a large number of aquaculture facilities are found in fjords, and fjords make up a recreational area for millions of Norwegians. With a few exceptions, Norwegian fjords include a sill near the opening. The sill is essential for almost all fjord processes: it forms a barrier for the deep water in the fjord, which has a strong impact on the stratification there. The sill barrier also strongly influences the water mass exchange between the fjord and the ocean in general, and the level of eutrophication in the fjord in particular. Thus, the sill is an obstacle for sediment transport, and its presence is vital for the oxygen conditions in the fjord’s deep water. Thus understanding, and being able to model, the spatio-temporal variability of mixing in a fjord is essential in any study that involves marine ecology. This is particularly true when effects of projected changes in the fjord’s physical environment are investigated.

In this thesis we examine the causes of and regional distribution of mixing in the Oslofjord (Fig. 1). A primary focus is on the generation of internal waves at the sill and their contribution to turbulent mixing. This is performed by 1) applying novel techniques in numerical modeling, 2) conducting a dedicated observational campaign, and 3) analyses of observations and model results.

2. Oxygen depletion and formation of hydrogen sulphide

The length of the period the deep water is stagnant inside of the sill has received considerable attention due to its impact on the oxygen conditions in the deep water. Already at the beginning of the 1900 century Gaarder (1916) described how the fjords of western Norway was aerated. He observed how the oxygen concentration in the depths varies with deep-water renewals. The main process consuming oxygen in the deep water is the decomposition of sinking organic matter, while the only supply of oxygen is the inflow of oxygenated water during deep-water renewals. If the consumption is greater than the supply, oxygen is depleted and hydrogen sulphide is produced.

In the inner Oslofjord the pollution situation was early on associated with limited water exchange. According to the book by Tor Are Johansen about the history of the waterworks and sewer in Oslo (Johansen 2001), a survey of the pollution situation was conducted around 1901 before the introduction of the water closet system. The question was if the fjord could withstand the increased pollution that such a system would entail. This survey was quite unusual at the time. Divers were used, and they reported that they sank down into the mud up to the armpits when they walked at the bottom. Professor of Hygiene and Bacteriology Axel Holst led the work, and the conclusion was that the pollution already was so severe that cleaning of the sewage discharge was necessary anyway. Holst relied on previous studies in the fjord (Hjort and Gran 1900) where it had been found that water exchange was limited.

Despite the construction of sewage treatment plants, it became over the years more and more evident that the pollution pressure was too great for the fjord. Braarud and Ruud (1937) found hydrogen sulphide at 150 meters depth and very low oxygen values at 100 m in 1933. Beyer and Føyn (1951) reported high oxygen consumption and formation of hydrogen sulphide in the bottom area up to 70 meters. This situation had dramatic consequences, for instance for the shrimp fishing. Gade (1967) explained why the Bunnefjord was particularly vulnerable. Measurements of density profiles over several years in both the Vestfjord and the Bunnefjord showed that time rate of change of salinity in the deep water was much slower in the latter basin (Fig. 2). Inspection of Fig. 2 shows clearly that the density decreases more rapidly in the Vestfjord than in the Bunnefjord during stagnant periods, and that the deep-water renewals occur more often in the Vestfjord. The Bunnefjord basin is therefore more vulnerable to the increased oxygen-consuming pollution, since the deep water is stagnant for longer periods. The question that still remains is why the mixing conditions are so different in the basins.

3. The importance of internal waves in sill fjords

Vertical oscillations of surfaces of constant density in the interior of a fluid are called internal waves. Internal waves can be generated when currents interact with bottom topography. One example of this is when tidal currents pass across a sill inn a fjord. Internal waves have been studied sporadically in the Oslofjord. Thus the first field campaign in the PhD project was dedicated to describe how internal waves are generated at the sill and radiate away from it (Staalstrøm et al. 2012).

a. Conditions for deep-water renewal

Many fjords have basins that are separated by an underwater ridge limiting the exchange with water masses outside the fjord. Such fjords are called sill fjords. Because of freshwater supplied to the fjord basins, fjords are generally well stratified. This implies that the density increases with depth and thus that the vertical movements are restricted by gravity. Hence water residing inside the sill remains there until heavier water spills over the sill. This happens when winds of sufficient strength and duration blowing out of the fjord causes the heavier water masses outside of the sill to be uplifted. Inflow of increasingly heavier water will over time make deep-water renewals impossible, since there is an upper limit to the density of the inflowing water. The only process capable of reducing the density of the deep water is by vertical mixing in which fresh water higher up in the water column is mixed with the heavier deep water and thereby decreasing the density there. This mixing process is commonly referred to as turbulent diffusion, acknowledging that it is the turbulence in the water columns that contributes to the mixing. If the vertical mixing goes on for a long enough period, the density in the deep water will be sufficiently reduced so that the heavier water spilling over the sill may penetrate all the way to the bottom of the basins. Thus the vertical turbulent diffusion paves the way for deep-water renewals.

To mix water vertically requires energy. Turbulent diffusion in the fjord basins therefore depends on how much energy there is available for generating turbulence. In some fjords the sill is so shallow and the mixing so weak that deep-water renewals practically never occurs. This is for example the case in the small fjord Framvaren in the southern parts of Norway (Piper 1971, e.g.). This is also true for the the Black Sea (Degens and Ross 1972, e.g.), which in many ways may be considered a sill fjord. In contrast the mixing in other fjords is so powerful that the deep water is replaced almost continuously. Between these two extremes there are fjords with an alternation of stagnant periods with mixing and shorter periods with deep-water renewals. This is for example the case in the Oslofjord.

As depicted in Fig. 1 the inner Oslofjord north of the sill at Drøbak is divided into multiple basins. The different basins may be categorized according to their mixing conditions. In the innermost basin (the Bunnefjord) there are several years between every deep-water renewal, while in the Vestfjord, which is closer to the sill, a deep-water renewal normally occurs every winter. Even closer to the sill there are smaller basins where the deep water is replaced even more often.

b. Source of energy for turbulent diffusion

We have observed that mixing conditions are different in the different basins of the Oslofjord, and it has been pointed out that the vertical mixing requires energy, since the result is that mass is lifted up against gravity. Where does this energy come from? Wind drag on the surface is an energy source for mixing in the upper layer. This process homogenizes the top layer. Hence the density difference between the water masses above the pycnocline, which separates the upper layer from the deep water, becomes even larger and makes it even more difficult to mix up the water from deeper waters. The barotropic tidal wave has enormous amounts of energy, but is distributed throughout the whole water column. In addition the wave moves with a phase velocity of 30-50 m s^{-1} so that the water level over large areas is lifted almost simultaneously. The result is that all this water flows into and out of the fjord during one tidal period. The mixing process uses only a fraction of the kinetic energy that is present in the tide. In the course of a tidal period there is a large energy flux into the fjord, and an almost equally large energy flux out. Since the energy flux out of the fjord is not exactly the same, some of the energy remains and is transformed into other forms of energy, e.g., internal waves.

c. Internal waves

The simplest form of internal waves is the vertical oscillation of the interface between two layers of different density. It was early known that tidal flow over a sill forms internal waves. Zeilon (1912, 1913) presented observations in the Gullmarfjord on the west coast of Sweden that showed this, and also studied the phenomenon in a wave tank. Gade (1967) presented similar observations from the Oslofjord. Stigebrandt (1976) explained how internal waves occur in a simple model with two layers and a sill that blocks the lower layer. The wavelength of the tidal surface wave is so long that currents are set up all the way down to the bottom. In the lower layer, this flow is stopped by the sill. The result is internal waves that propagate away from the sill and sets up a current in the lower layer at the position of the sill that balance the current in the lower layer generated by the barotropic tide. These internal waves will have the same period as the surface tide and is therefore called tidally-induced internal waves or internal tides as displayed in (Fig. 3) showing observed internal tidal waves at two positions in the inner Oslofjord from the first field campaign as presented in the first paper in of the thesis (Staalstrøm et al. 2012). We note that there are considerable vertical oscillations in the water at the station Kaholmen located approximately 1 km inside of the main sill. At the station Søndre Langåra about 10 km inside the main sill there are also vertical oscillations, but the amplitude is significantly reduced.

Another noteworthy point is that the peaks and troughs of the internal waves are nearly 2 hours delayed at the innermost station, suggesting that the phase velocity of the dominant internal wave is slightly higher than 1 m s^{-1}. The figure thus tells us two things, namely that the internal waves transport energy into the fjord and that some of this energy is lost along the way. Based on measurements of vertical oscillations of density surfaces at one station it is not possible to see which way the energy moves. To determine the direction it is necessary to look at the velocity field set up by the internal waves. In (Fig. 4a) the density contours from station Kaholmen have been drawn on top of the velocity field measured at the same station. In a two-layer model the internal wave will set up a velocity field which is oppositely directed in the upper and lower layer.

A pressure field will also be created. When the interface is lifted upwards, the pressure increases in the lower layer and decreases in the upper, and when the interface is pushed down, the opposite is happening. In this case the energy flux may be considered as a transport of pressure, meaning that if the current in the upper layer is directed into the fjord at the same time as it is high pressure in this layer, and out of the fjord when it is low pressure, the energy will be carried into the fjord. Based on Fig. 4, it is apparent that this is the case here.

In the first work (Staalstrøm et al. 2012) we estimated by this method the energy flux at station Kaholmen, averaged over a spring-neap cycle in August 2009, to be in the range 190 ± 90 kW directed into the fjord. The method used to derive these results is described in the third paper

(Staalstrøm and Røed 2015). This energy is drained from the barotropic tide. Stigebrandt (1976) suggested that the internal waves carry energy into the fjord and break when they encounter the sloping bottom at the head of the fjord. In this way the tidally-induced internal waves transform the energy contained in the imposed barotropic tides into turbulence and hence contributes to vertical mixing inside of the main sill.

d. Dissipation at the Drøbak Sill

When water flows over the Drøbak Sill into the fjord, the pycnocline is lifted outside of the sill and pressed down on the inside. With an outward flow the opposite will happen, in agreement with the simple model presented by Stigebrandt (1976). The problem is that in this scenario strong horizontal pressure gradients across the sill will be created, possibly resulting in a jet flow that may develop severe turbulence.

Fig. 5 shows measurements of dissipation in a section across the Drøbak Sill during an influx. Measurements were conducted from the R/V Trygve Braarud, in cooperation with the University of Gothenburg, using a drop-sonde that measures fine-scale velocity shear. Dissipation is an expression of the kinetic energy lost to other forms of energy in the water and is measured in W kg^{-1}. The energy that goes into this process is also drained from the barotropic tide.

By integrating the dissipation in a volume inside the sill and multiplying with the density of the water mass, an estimate of how much energy that is involved may be estimated. In the second paper (Staalstrøm et al. 2015) data from several such transects (Fig. 5), at various stages of the tidal cycle, are used to estimate that about 530-790 kW of the tidal energy is lost to friction. While this value is considerably higher than the energy contained in the internal waves, this energy is not as important for the mixing further into the fjord, since it is not transported anywhere.

e. Modelling of internal tides and dissipation

Density surfaces are drawn on top of observations of dissipation in Fig. 5. Across the Drøbak Sill they are almost vertical. This indicates substantial vertical velocities. In a typical ocean model, such as the one used in the third paper, the hydrostatic approximation is used. This entails that it is assumed that the influence of vertical acceleration on the pressure in the water column does not need to be taken into account. This is usually a good assumption in the ocean, but in some areas such as the Drøbak Sill this is not valid. Since hydrostatic models are so widely used, it is therefore interesting to see how well such models can simulate the energy flux of the internal waves at a distance away from the sill.

In the third paper (Staalstrøm and Røed 2015) it is tested how well a hydrostatic model can reproduce observed currents inside the Drøbak Sill. Fig. 4b shows the data obtained from this ocean model which is set up for the Oslofjord on a grid with a mesh size of 75 meter. Data are from a station in the model that corresponds to the station Kaholmen. By comparing the vertical oscillation of the density surfaces and the flow field of the internal waves from observations and model results, it is seen that the model is able to reproduce the energy flux, despite the fact that details of the current field at the Drøbak Sill is not entirely correct. Since the model is able to reproduce the conditions at this station, one can assume that it is possible to extract information about the energy flux in other parts of the fjord as well. This information may then be used to answer questions about the mixing conditions in the inner Oslofjord. In fact it is used to explain why the different basins have different mixing conditions. It is also found that even if the vertical displacement of density surfaces decrease when stratification is increased, the energy flux away from the sill increases. The reason for this is that more energy is required to displace density surfaces in strong stratification than in weak. In this way wind-mixing of the surface layer, that strengthen the pycnocline and makes it more difficult to mix up deeper waters, actually indirectly enhance the turbulent vertical mixing in sill basins, since internal waves are transported more efficiently.

f. An explanation of why the different basins have different mixing conditions

Earlier we asked ourselves the question why diffusion is different in different basins of the inner Oslofjord. It was hypothesized that the energy carried into the fjord with internal waves was lost to turbulent production on the way. The internal waves contribute to the very high diffusion in the first basin in the Vestfjord just inside the Drøbak Sill, so that the deep-water renewals may occur almost every winter. But when the internal waves reach the Bunnefjord there is very little energy left for vertical mixing. To quantify this, we extracted data from different cross sections of the fjord and calculated the energy fluxes (Staalstrøm and Røed 2015). Fig. 6 demonstrates that the energy flux becomes smaller and smaller as one moves into the fjord, and this explains why the resulting mixing also is different.

4. Sill fjords as models for the world ocean

Just as the vertical circulation in a sill fjord depends on vertical mixing, the meridional overturning circulation in the world oceans depends on mixing to lift the heavy deep water up from the depths. In the world oceans deep-water formation takes place at high latitudes when seawater is cooled and possibly becomes more salty because of ice formation. This mechanism can be compared with the inflow of heavy water during a deep-water renewal. As the circulation in a sill fjord would come to a halt, the same would happen in the ocean if there was not sufficient vertical mixing. Eventually it would not be possible to form water that was heavier than the water already lying in the depths. Fortunately, also in this case the tide offers enough energy to provide the necessary mixing. And it is the same phenomenon that stands as a link between tidal surface waves and the mixing in the depths, namely the internal waves. Since we have focused on the

Oslofjord it is worth mentioning that one of the first attempts to quantify the impact of internal waves on the circulation of the oceans was inspired by work originally done in the Oslofjord (Sjöberg and Stigebrandt 1992).

5. Summary of the papers

a. PAPER 1: Propagation and dissipation of internal tides in the Oslofjord

Observations of velocity, pressure, temperature and salinity in the inner Oslofjord have been analysed to provide new information about the relationships between internal tides generated by tidal currents across the Drøbak Sill and dissipation and diffusivity in the fjord. The most energetic vertical displacement of density surfaces inside the sill is associated with the first internal mode that has maximum amplitude around sill depth. The amplitude of the vertical displacement around sill depth correlates with the amplitude of the surface elevation, and at a distance of 1 km inside the sill the ratio between the amplitudes is 38, decreasing to 11 at a distance of 10 km. The greatest vertical displacements inside the sill, however, are found at 40 m depth. These latter internal waves are not associated with a first mode internal tide, but are associated with higher internal modes controlled by stratification. The energy flux of the internal wave propagating from the Drøbak Sill into the inner fjord on the east side of the Håøya Island is estimated to vary in the range 155-430 kW. This is the same order of magnitude as the estimated barotropic energy loss over the Drøbak Sill (250 kW), but contains only 4-10 % of the total barotropic flux. Approximately 40-70 % of the internal energy flux is lost within a distance of 10 km from the sill. The mean diffusivity below 90 m depth in this area (20 cm^2 s^{-1}) is more than four times higher than in the rest of the fjord (5 cm^2 s^{-1} or less).

b. PAPER 2: Observations of turbulence caused by a combination of tides and mean baroclinic flow over a fjord sill

Investigated is the dissipation rates and flow conditions at the Drøbak Sill in the Oslofjord. The area was transected 13 times with a free falling microstructure shear probe during 4 days in June 2011. At the same time an ADCP was deployed inside the sill. During most tidal cycles, internal hydraulic jumps with high dissipation rates were found on the downstream side of the sill. However, the internal response varied strongly between different tidal cycles with similar barotropic forcing. In the beginning of the observational period, ebb tides had no hydraulic jumps, and in the end one of the flood tides did not have a hydraulic jump. During the same period the mean baroclinic exchange flow changed from inflow to outflow in the bottom layer. We conclude that the conditions at the sill are on the edge of forming hydraulic jumps, and that the mean baroclinic exchange may push the flow above or below the limit of a hydraulic jump depending on the situation. This conclusion is supported by two-layer hydraulic theory. The volume integrated dissipation rates within 500 m from the sill crest compare well with estimates of energy loss in the lower layer calculated from the Bernoulli drop under the assumption of no energy loss in the upper layer. Finally, the mean dissipation rate at the sill was compared with the radiation of internal tidal energy away from the sill and it was found that about 60-90 % of the total energy loss was dissipated locally.

c. PAPER 3: Internal wave energy fluxes and vertical mixing in a sill fjord

To investigate tidally-induced, propagating internal waves in a sill fjord we employ an eddy-resolving version of the three-dimensional, hydrostatic ocean model ROMS. In particular we use the model results to study the distribution and level of local vertical mixing in the fjord. The work is motivated by observation of long periods (e.g., years) of hypoxic or even anoxic conditions in the innermost basin in the Oslofjord, Norway. These episodes are attributed to too weak vertical mixing in the innermost basin, a mixing that is much weaker then in the basins closer to the sill. The question that arises is why this is so. Our hypothesis is that the local vertical mixing level inside of the sill is determined by the loss of energy of propagating, tidally-induced internal waves whose source is the sill region. To support our proposition we perform simulations in which we generate the propagating, internal waves by specifying the barotropic tides well outside of the sill. In fact we find that the internal waves loose most of their energy before they reach the innermost basin and thus explains the difference in mixing between the basins.

To calibrate and tune the model for the purpose at hand we perform a number of experiments in which the impact of changing the mesh size and various parameters and parameterizations is investigated. We also evaluate the model results by comparing them to observations inside of the sill as well as in the vicinity of the sill. We find for instance that it is important to choose a mesh size small enough to appropriately resolve the dominant wavelength of the topography. Moreover, we find that the strenght of the turbulence production and hence the mixing depends on the initially chosen stratification. In addition we find that it is important to minimize the pressure gradient error in the upper water masses. The latter lead us to suggest a new transform and stretching in ROMS. Finally, we note that the method we use is generic and may be applied to any sill fjord.

6. Concluding remarks

a. Summary of the main results

By using field observations and numerical modelling it has been shown that the vertical diffusivity in different parts of the Oslofjord is related to internal waves that are created at the Drøbak Sill. The internal waves carry energy away from the sill and gradually lose this energy during propagation into the fjord. When the waves reach the innermost basin, very little energy is left for vertical mixing. This causes the water mass in the deeper parts of the Bunnefjord to be stagnant for years. This is in contrast to the Vestfjord where the deep water is stagnant for only parts of the season. In the Bunnefjord the weak vertical mixing leads to hypoxia, defined as water with lower than 30 % oxygen saturation, or even anoxia, defined as water with zero oxygen saturation. The consequence of this is that all higher forms of life disappears. At the time of writing (December 2015), the conditions in the Bunnefjord is on the brink of reaching anoxia (Fig. 7).

In the first paper the propagation and the loss of energy flux are described with field observations of the vertical stratification and current profiles. In the second paper details on the relation between dissipation in the vicinity of the Drøbak Sill and energy flux that radiates away from the sill, is studied with a drop sonde measuring vertical velocity shear. In the last paper energy flux is modelled with a high-resolution three-dimentional, hydrostatic model for the Oslofjord. The results clearly show the relationship between the loss of internal wave energy and vertical diffusivity.

b. Future work

Even though a relationship between the loss of internal wave energy flux and vertical diffusivity is shown, details on where and when the internal waves break and release energy that are made available for vertical mixing, are still not entirely clear. The hydrostatic model that is used in this project is not capable of describing the breaking process directly, even though turbulent dissipation is parameterized. It is also a challenge to observe this process directly, even though attempts are made to observe breaking internal waves with dye release (Inall 2009). A possible approach could be to conduct a measurement campaign combining drop sonde with moored instrument rigs in an area where internal waves are expected to break, based on parameterized dissipation from model results.

Another question is why basins with narrow and shallow entrances with extremely high current velocities, and also a high loss of barotropic energy, usually have low levels of vertical mixing in the deep water. In light of this thesis we can narrow this question down to why internal waves do not radiate away from such sill areas. An example of this is the Drammensfjord, where the current speed over the Svelvik Sill reach several m s^{-1}, while the diffusivity in the main basin is lower than in the Bunnefjord. The Drammensfjord is particularly interesting since the Svelvik Sill was dredged a few years ago, followed by re-oxygenating of the deep water. Wether or not the diffusivity have changed, or if the re-oxygenation was due to the cold winters in this period that made favorable conditions for deep water renewals, is still unanswered.

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3 The figure shows how the density at station S2 (upper panel) and S5 (lower panel) varies during 24 hours between 13 and 27 m depth. The colour scale indicate the density in kg m^{-3}. The contour line for the 1023 kg m^{-3} density surface is drawn with a black line. The vertical lines indicate the time when the first maximum occurs at each station. 22

4 Comparison between observations (upper panel) and model calculations (lower panel) of current speed along the channel and density surfaces at station S2. The colour scale indicates the current speed in m s^{-1}. Red colour indicates currents directed into the fjord, and blue currents directed out of the fjord. The black lines are density surfaces. Note that the current is directed into the fjord at the same time as density surface depressions. 23

5 Dissipation in a transect along the channel passing the Drøbak Sill as well as the second sill. Dissipation is measured with a micro structure drop sonde during an inflow. The colour scale indicate the dissipation on a logaritmic scale with the range from 10^{-9} to 10^{-3} W kg^{-1}. The black contour lines are density surfaces, and the crosses indicate the approximated posistions of the dissipation measurements. The current profile measured at station S2 is shown with arrows. 24

6 Internal wave energy flux and average eddy diffusivity coefficients in closed basins in the Oslofjord. The internal wave energy flux is calculated in seven selected cross sections of the fjord is calculated for a weak and a strong stratification. The results in units of kW is adjacent to the seven arrows, where the highest values apears when the stratification is strong. The eddy diffusivity coefficient between 90 and 125 m depth is calculated for the four different basins labeled H2, H3, H4 and H5. The values for each basin is given in each box. 25

7 Time series of oxygen content in ml/l in the Bunnefjord (red curve) and the Vestfjord (blue curve) for the period January 1990 through December 2014. Note the long periods of anoxic and hypoxic events in the Bunnefjord compared to the short period of hypoxic events in the Vestfjord. Courtesy of Jan Magnusson and Anna Birgitta Ledang, NIVA. 26

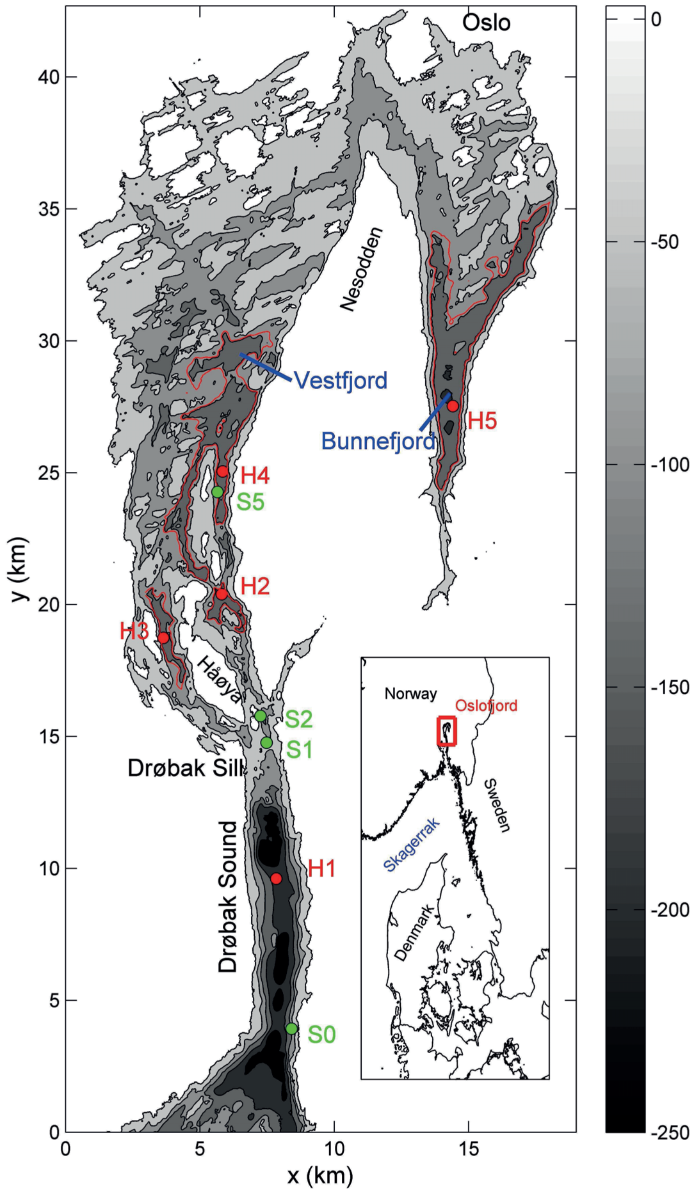

FIG. 1. Map of the Inner Oslofjord. Depth contours are drawn for every 50 m. The green horizontal line at the bottom of the graph marks the southern open boundary of the model. Moorings were deployed at stations S2 and S5 in 2009 (marked with green circles). Stations H1, H2, H3, H4 and H5 marked with red circles are standard hydrographic stations from the monitoring program. Four different basins are separated by the 90 m depth contour (red line). The maximum depth in the model area is 214 meter (in the Drøbak Sound south of the Drøbak Sill) and the shallowest depth is 20 meters which is the Drøbak Sill.

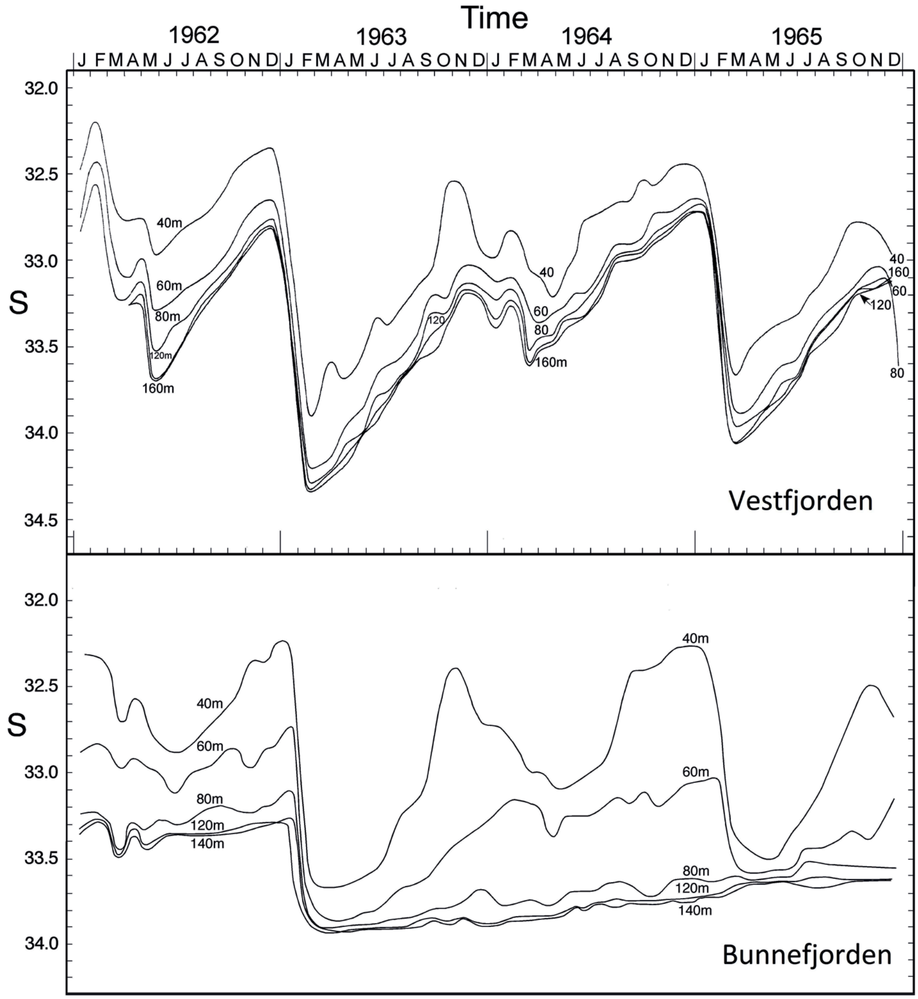

FIG. 2. Salinity at different depths at station H4 in the Vestfjord (upper panel) and at station H5 in the Bunnefjord (lower panel). The figure is from Gade (1967). It is apparent that the vertical mixing is higher in the Vestfjord than in the Bunnefjord.

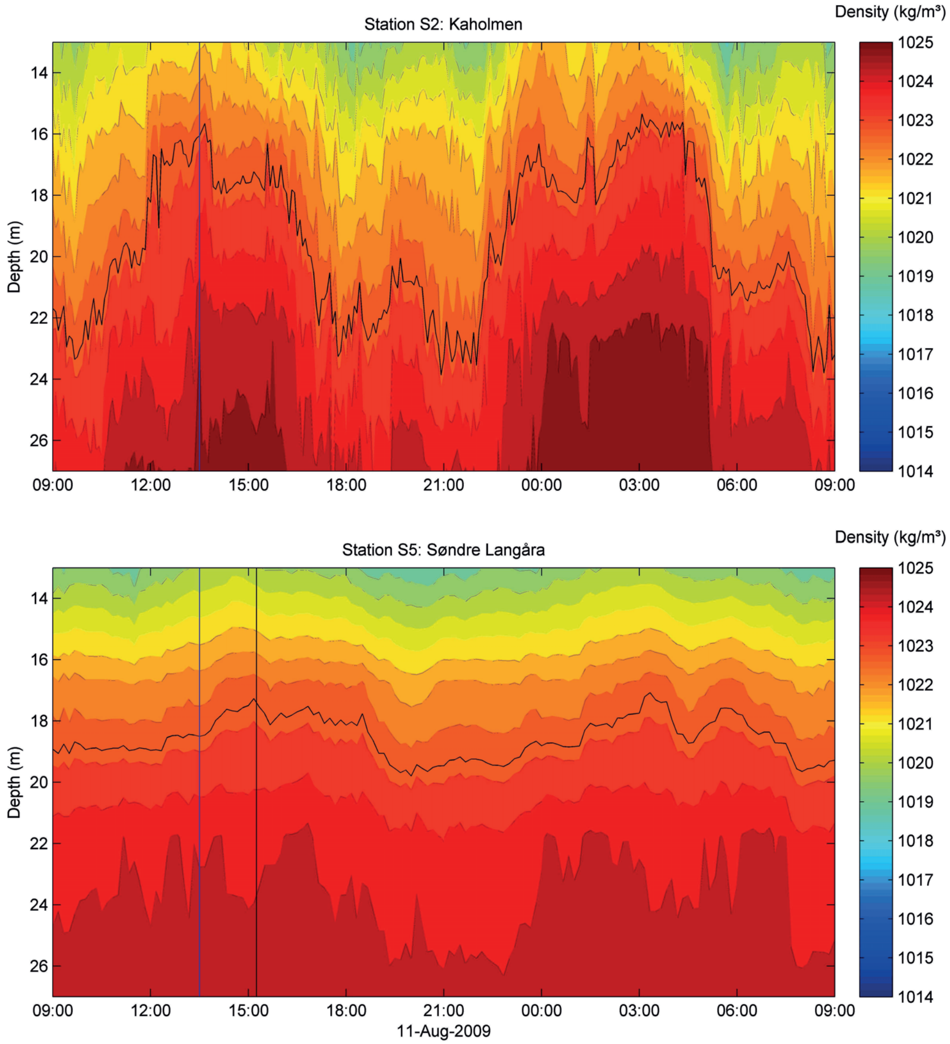

FIG. 3. The figure shows how the density at station S2 (upper panel) and S5 (lower panel) varies during 24 hours between 13 and 27 m depth. The colour scale indicate the density in kg m^{-3}. The contour line for the 1023 kg m^{-3} density surface is drawn with a black line. The vertical lines indicate the time when the first maximum occurs at each station.

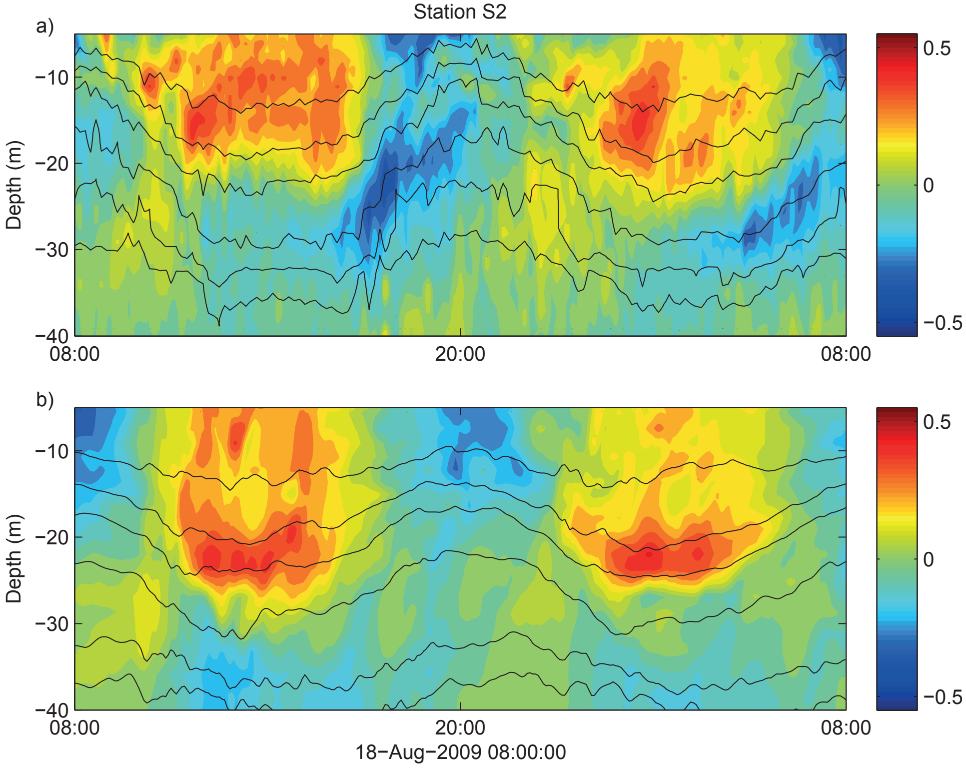

FIG. 4. Comparison between observations (upper panel) and model calculations (lower panel) of current speed along the channel and density surfaces at station S2. The colour scale indicates the current speed in m s^{-1}. Red colour indicates currents directed into the fjord, and blue currents directed out of the fjord. The black lines are density surfaces. Note that the current is directed into the fjord at the same time as density surface depressions.

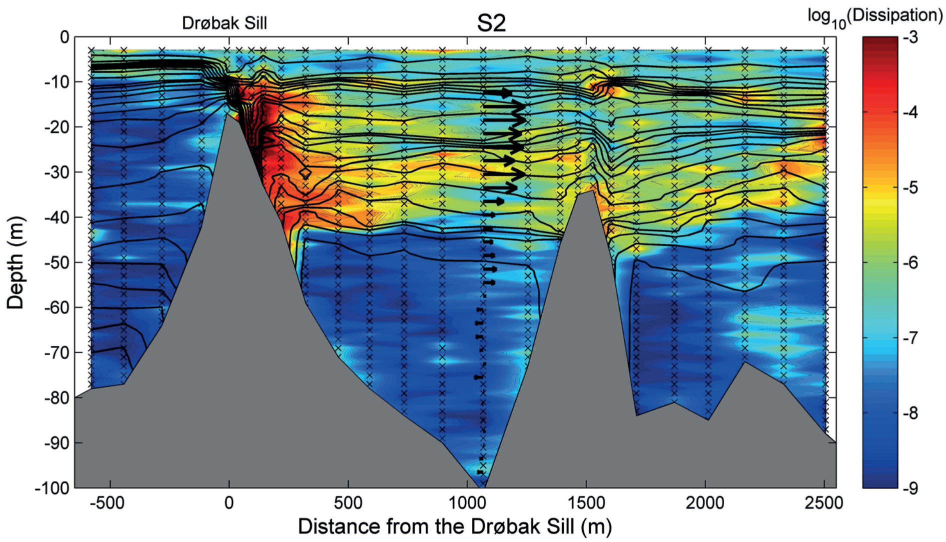

FIG. 5. Dissipation in a transect along the channel passing the Drøbak Sill as well as the second sill. Dissipation is measured with a micro structure drop sonde during an inflow. The colour scale indicate the dissipation on a logaritmic scale with the range from 10^{-9} to 10^{-3} W kg^{-1}. The black contour lines are density surfaces, and the crosses indicate the approximated posistions of the dissipation measurements. The current profile measured at station S2 is shown with arrows.

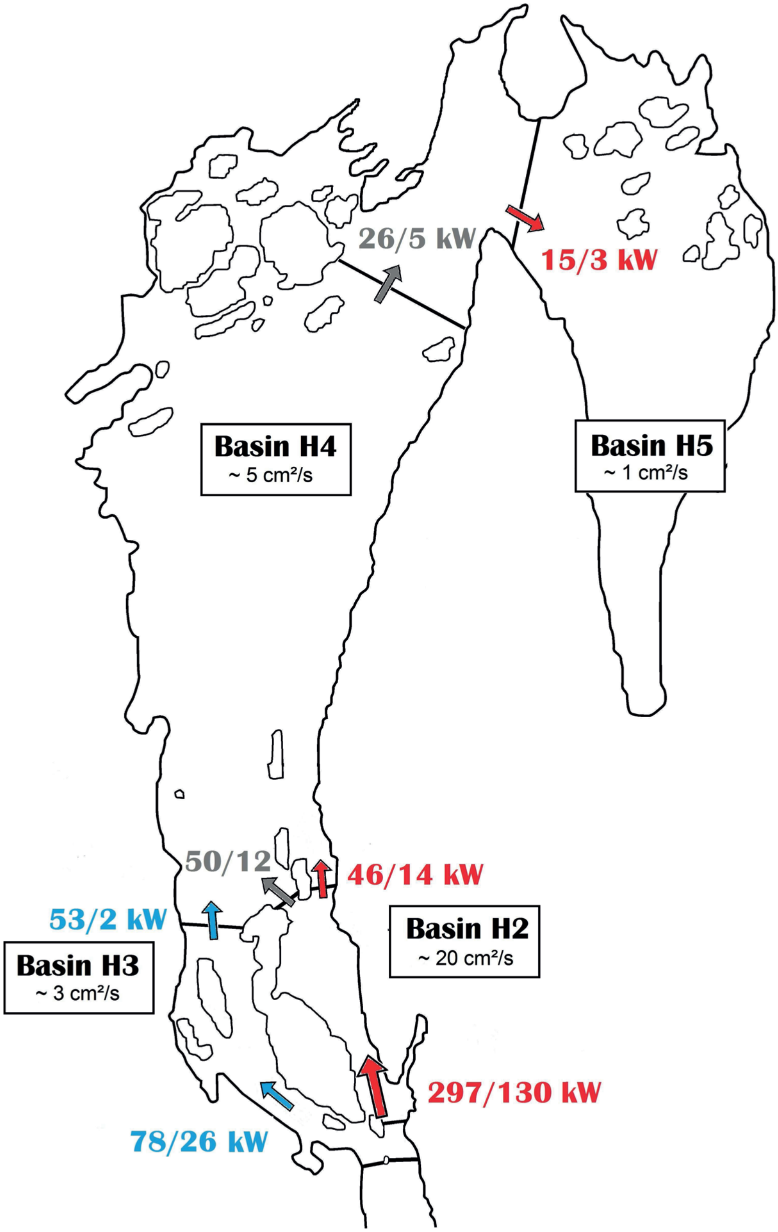

FIG. 6. Internal wave energy flux and average eddy diffusivity coefficients in closed basins in the Oslofjord. The internal wave energy flux is calculated in seven selected cross sections of the fjord is calculated for a weak and a strong stratification. The results in units of kW is adjacent to the seven arrows, where the highest values apears when the stratification is strong. The eddy diffusivity coefficient between 90 and 125 m depth is calculated for the four different basins labeled H2, H3, H4 and H5. The values for each basin is given in each box.

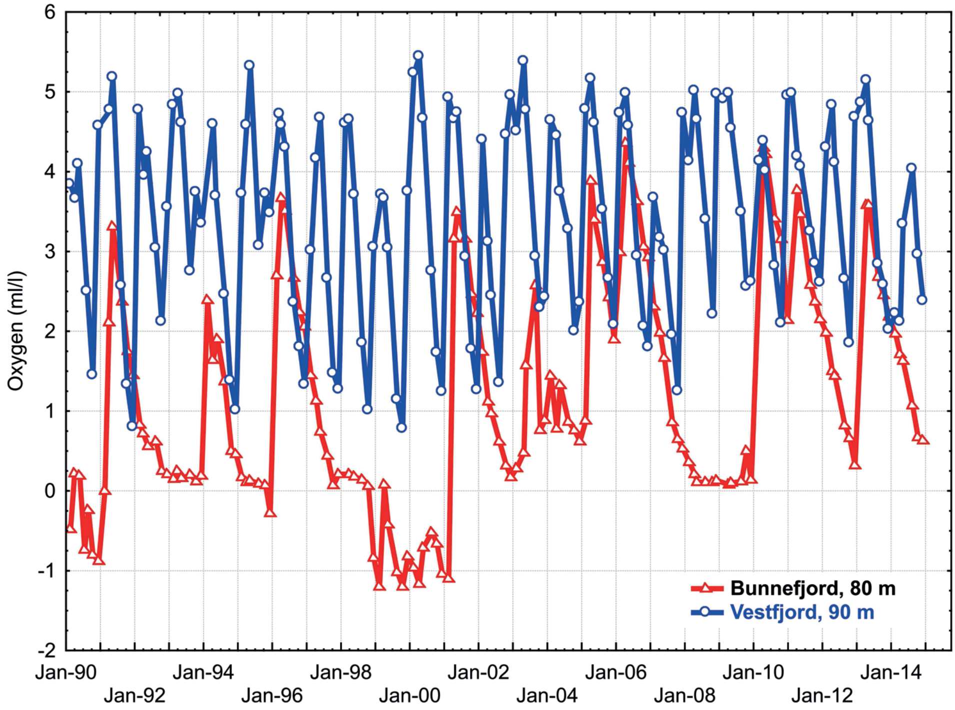

FIG. 7. Time series of oxygen content in ml/l in the Bunnefjord (red curve) and the Vestfjord (blue curve) for the period January 1990 through December 2014. Note the long periods of anoxic and hypoxic events in the Bunnefjord compared to the short period of hypoxic events in the Vestfjord. Courtesy of Jan Magnusson and Anna Birgitta Ledang, NIVA.